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AMTAS
Advanced Materials in Transport Aircraft Structures

Failure of Notched Laminates Under Out-of-Plane Bending Phase IX

Fall 2015 Meeting

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Failure of Notched Laminates Under Out-of-Plane Bending. Phase IX

- Motivation and Key Issues

  Develop analysis techniques useful in design of composite aircraft structures under out-of-plane loading (bending and shear)

- Objective

  Determine failure modes and evaluate capabilities of current models to predict failure

- Approach
  - Experiments: Out-of-plane shear (mode 3 fracture)
  - Modeling: Progressive damage development and delamination (Abaqus) under Mode 3 fracture

Failure of Notched Laminates Under Out-of-Plane Bending. Phase IX

- Principal Investigators & Researchers
  - John Parmigiani (PI); OSU faculty
  - M. Daniels, L. Suryan; OSU grad students
- FAA Technical Monitor
  - Curt Davies
  - Lynn Pham
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - Gerry Mabson, Boeing (technical advisor)
  - Kazbek Karayev , Boeing(technical advisor)

Project Overview

Phase I (2007-08)

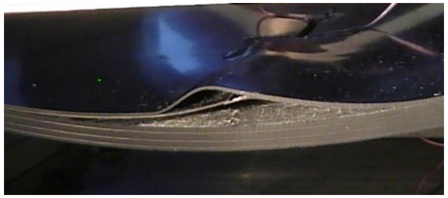
- Out-of-plane bending experiments w/composite plates
- Abaqus modeling with progressive damage

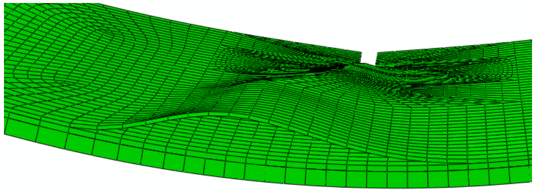
Phase II (2008-09)

- Abaqus modeling with buckling delamination added
- Sensitivity study of (generic) material property values

Phase III (2009-10)

- Abaqus modeling w/ more delamination interfaces





Project Overview

Phase IV (2010-11)

- Further study of additional delamination interfaces
- Sensitivity study using Boeing mat'l property values

Phase V (2011-12)

- Out-of-plane shear (mode III) experiments
- Evaluate the Abaqus plug-in Helius for out-of-plane bending

Phase VI (2012-13)

- Out-of-plane shear modeling with Abaqus Standard/Explicit
- Evaluation of plug-in Helius: MCT for out-of-plane shear

Project Overview

Phase VII (2013-14)

- Improvement to Abaqus Explicit models
- Explore damage softening parameters in Helius: MCT
- Explore possible inaccuracies in material properties

Phase VIII (2014-15)

- Explore significance of damage propagation material properties, i.e. when do energy parameters matter?
- Begin work on modeling matrix compression damage

Phase IX (2015-2016)

- Mode III Wrap up
- Matrix compression damage modeling and testing

Today’s Topics

- Wrap up for Mode III
  - Notch Sensitivity
  - Solid vs Shell Element Study
- Matrix Compression Failure
  - Literature Review
  - Testing Plan

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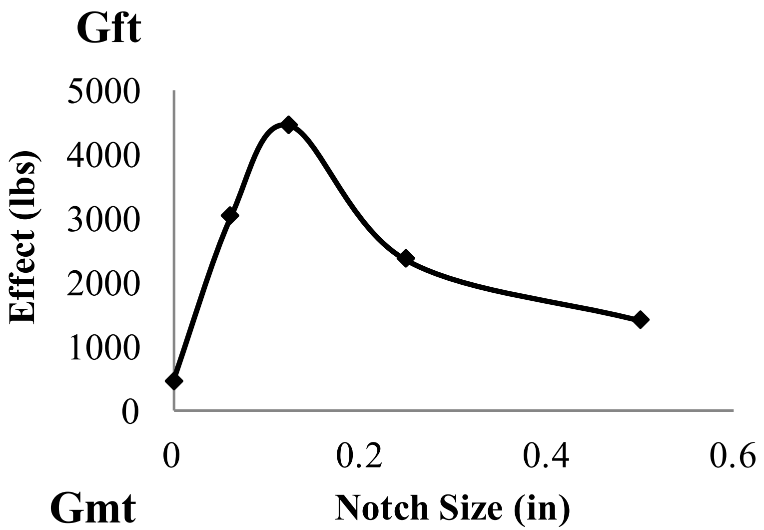
Notch Sensitivity

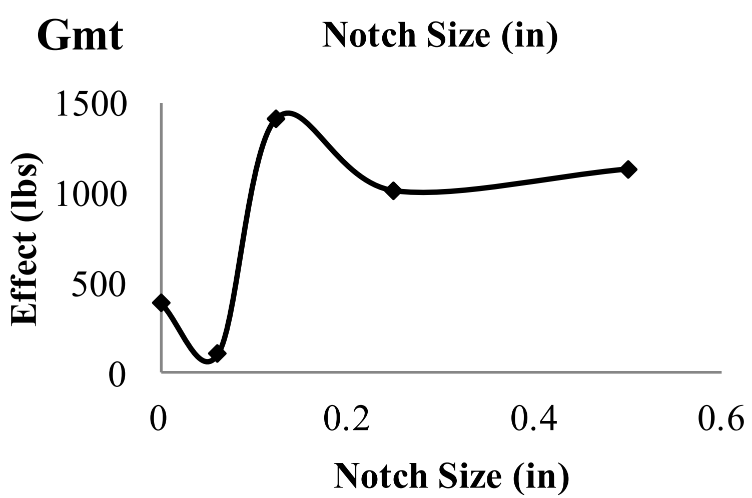
- The Hashin progressive damage model has been used in our work
- The model consists of 6 strength parameters and 4 energy parameters
- Sensitivity studies have led to interest in determining when the energy parameters are significant, specifically the effect of notch size.
- Goal: Determine effect of varying notch size on significance of energy parameters (Gft, Gmt, Gmc, and Gfc)
- Methods: Fractional factorial studies with 4 factors varied at ±50%

Gft	Energy required to fully damage the fibers in tension
Gfc	Energy required to fully damage the fibers in compression
Gmt	Energy required to fully damage the matrix in tension
Gmc	Energy required to fully damage the matrix in compression

Notch Sensitivity

- Results:
  - Notch size shown to have effect on energy-parameter significance.
  - Highly non-linear trends
  - Increased significance with decreasing notch size
  - Drop in effect at lower notch sizes possibly due to rapid failure across panel





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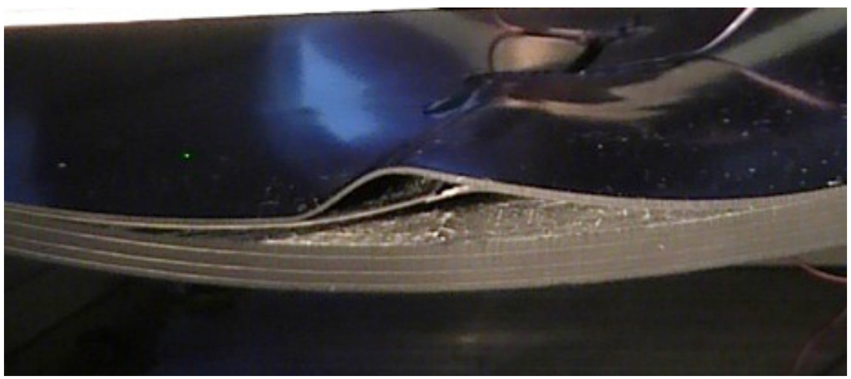
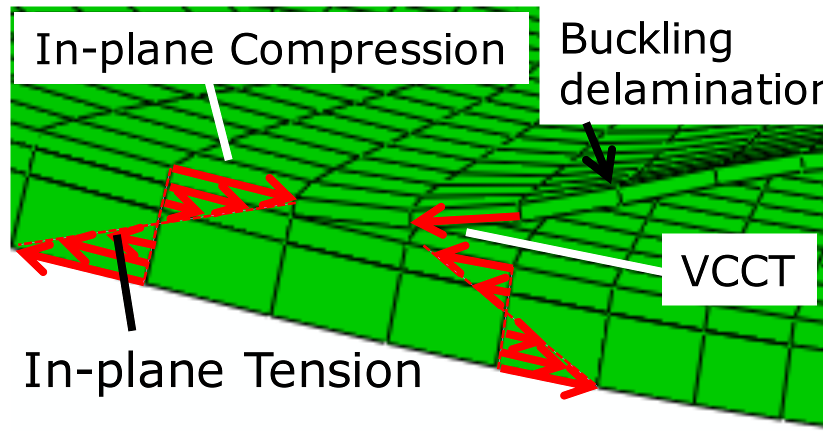
Solid vs Shell Study-Motivations

- Modeling approach worked better for out-of-plane bending than for out-of-plane shear
- Agreement between experimentally-measured and FEA-calculated maximum loads
  - Within 10% for bending
  - Within 25% for shear
- Also large differences between experimentally-measured and FEA-calculated notch-tip strain fields even for small displacements for Mode III
- Why?

Solid vs Shell Study-Motivations

- Out-of-plane shear is a more complicated than out-of-plane bending
- Under out-of-plane bending, the panel experiences out-of-plane applied loading, **but internal loading is primarily planar** (in the plane of the panel)

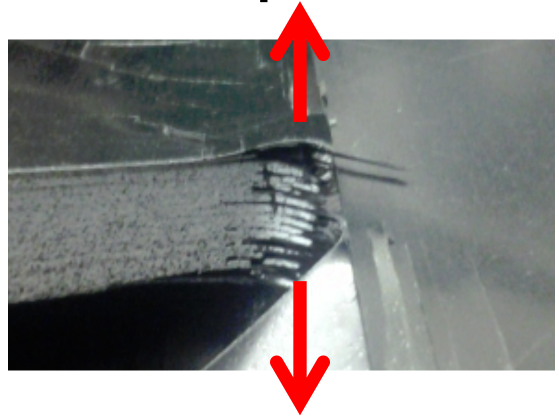




- Buckling occurs but is due to in-plane compression. Resulting crack propagation is modeled well with VCCT
- Abaqus continuum shell elements work well since they include planar response and allow for interfaces to model delamination

Solid vs Shell Study-Motivations

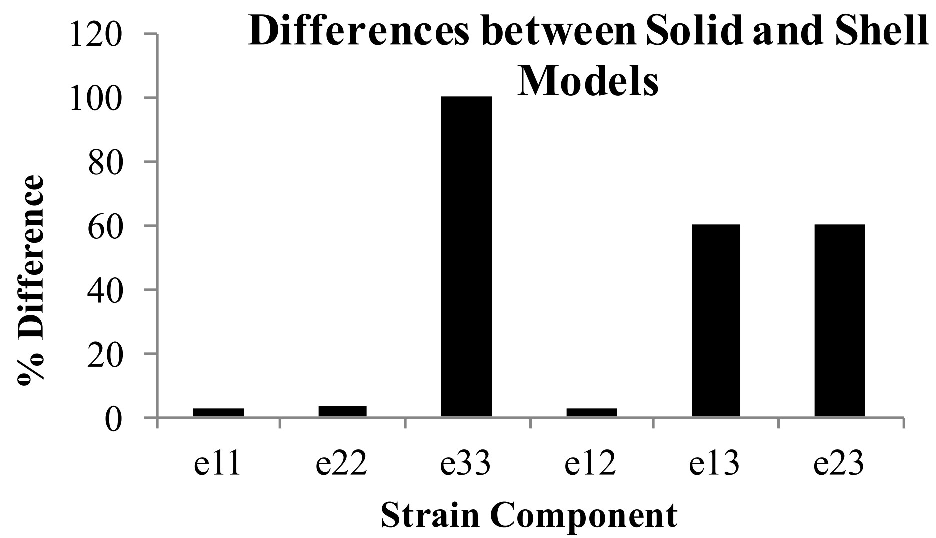
- Under out-of-plane shear, the panel experiences out-of-plane applied loading, **and significant out-of-plane internal loading at the notch tip**



- This is not in-plane compressive buckling, but is caused by out-of-plane normal strain.
- Abaqus continuum shell elements do not work well since they **do not include out-of-plane normal strain response**
- Goal: Study the effects of different element assumptions on the behavior of the panels loaded in out-of-plane shear

Solid vs Shell Study- Isotropic Plates

- Initially studied isotropic plates and compared to analytical solutions
- Solid and shell elements both showed agreement with analytical solutions for out-of-plane shear stresses within 5% when assumptions met (only out-of-plane shear)
- Still large difference between solid and shell models for the out of plane shear stresses
- No out-of-plane normal strains for shell elements

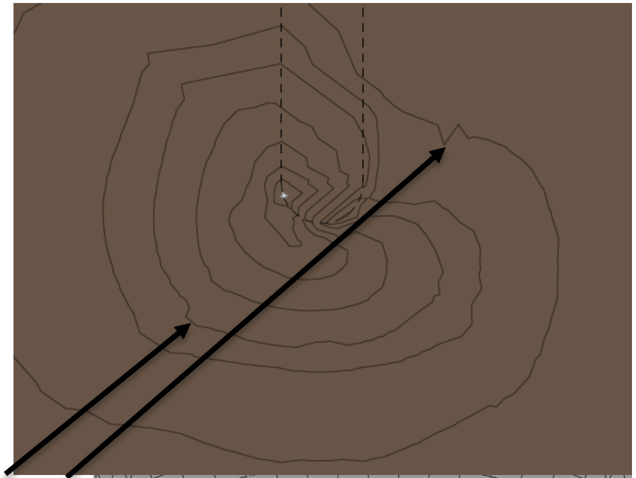


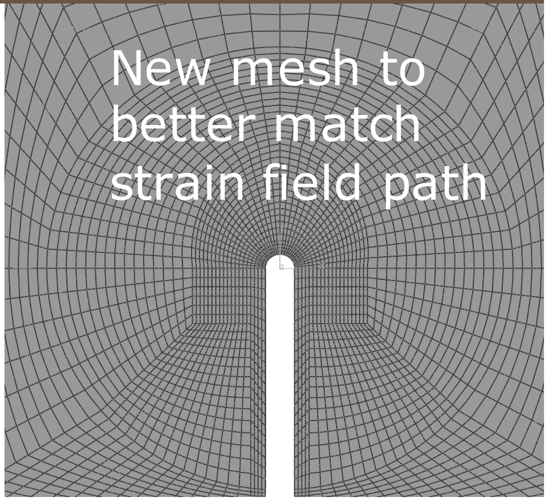
Solid vs Shell Study-Isotropic Plates

- Why the large difference between solid and shell out-of-plane shear when both agree with analytical model?
- FEA models focused on displacements since FEA and DIC comparisons were done at a specific displacement
- Solid and Shell elements predict different forces for the same displacement leading to different strain fields
- Possibly due to differences in bending assumptions
- Strain fields can differ greatly at the same displacement between solid and shell elements
- Since strain field at a displacement has been the metric in the past, solid and shell models differ greatly for these purposes
- Need to look at composite models and compare experiments

Solid vs Shell Study- Composite Plate Methods

- Extended study to composite plates under Mode III loading
- Composite layups able to be simulated with solid or shell elements, however no damage available for solid elements
- Several Improvement Methods Considered
  - Stacked Elements
  - Changing loading rates/simulation methods to
    better match experimental conditions
  - Change mesh-reduce mesh artifacts

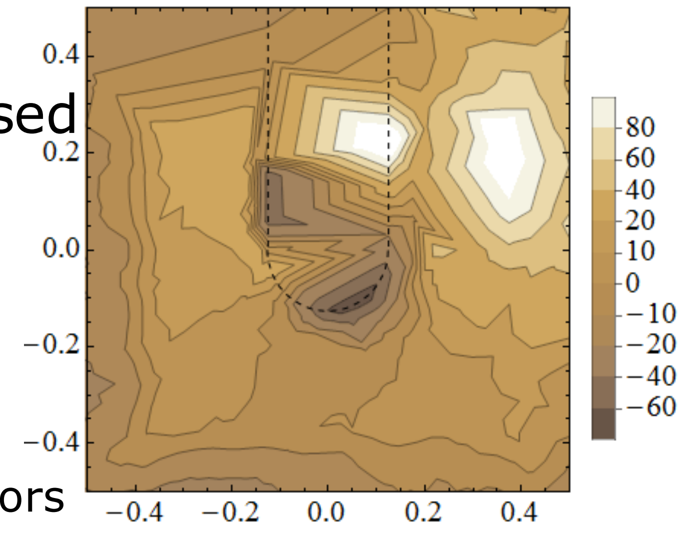




Solid vs Shell Study- Composite Plates Results

- Solid elements not able to achieve good agreement for composite plates-different strain field shape
- Little improvement with other methods
- Slightly better improvement with decreased loading rate or Standard Simulation
- Conclusions:
  - Differences between FEA and DIC due to simplifying out of plane shear response
  - Largest % errors in regions of low strain magnitude could be explained by round off errors and other low magnitude errors
  - Solid elements not recommended by Abaqus for composite shell modeling, difficulties with shell theories

Percent Difference Between FEA and DIC



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  - Notch Sensitivity
  - Solid vs Shell Element Study
- Matrix Compression Failure
  - Literature Review
  - Testing Plan

Matrix Compression Failure Motivation and Goals

- Possible uncertainties in damage propagation energy values sparked interest in further examination of the models
- Differences in interlaminar and intralaminar failure
- Currently fracture mechanics based approach
- Does a fracture model apply to compression loading?
- Initial literature reviews showed little for compression damage propagation in the matrix
- Goal: Design tests and numerical models to determine appropriate material model for compression damage propagation in a composite matrix

Matrix compression is a key element of composite failure and needs to be better understood

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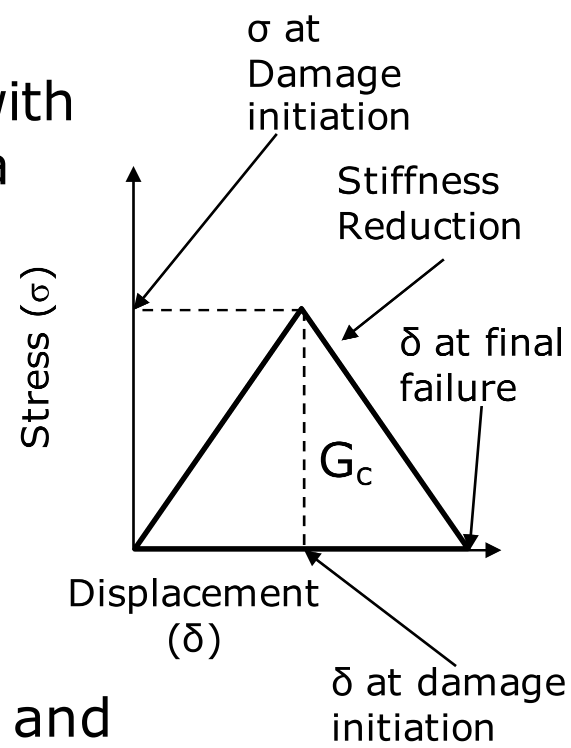
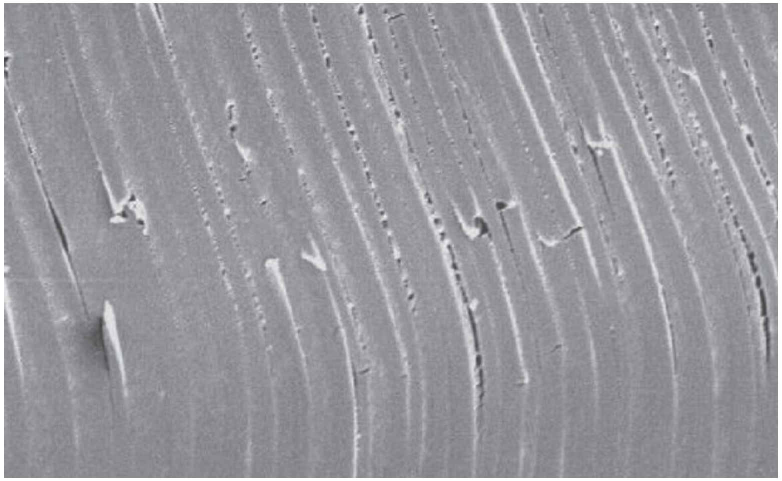
Literature Review- Current Abaqus Model

- Damage initiated by Hashin criteria
- Crack band model developed by Bazant and Oh
- Cracks modeled as several small cracks with the properties smeared across entire area (crack band)
- Stiffness reduction of elements based on damage variable
- Stress displacement law scaled based on element length and strength functions to ensure area under curve equal to the specified strain energy release rate
- Shear failure combination of compression and tension



Literature Review- Fiber Compression

- No studies found focusing on matrix compression
- Fiber kinking common area of study since 1980s
- Due to similarity in loading conditions some principles in fiber compression can be applied to matrix compression
- Kink bands are regions of micro-buckled fibers due to compressive loading
- General ideas and specimens can be applied to the matrix failure
- Partially governed by matrix response-Matrix supports fibers



Pinho et al On longitudinal compressive failure of carbon-fibre-reinforced polymer: from unidirectional to woven, and from virgin to recycled

Literature Review- Fiber Compression

- Fracture mechanics models applied to kink band (fiber compression) propagation
- Three different specimens commonly used to measure strain energy release rate:
- Center notched compression
  - Used primarily in early studies
  - Isolation of desired failure mechanism achieved in some studies, but specimens showed a tendency to split off axis
  - Require anti-buckling guards: face mounted or edge mounted
- Compact Compression
  - Modified versions of compact tension specimens
  - Good isolation of desired failure mode until significant crack growth
- Four Point Bending
  - Different failure mode: through thickness vs intralaminar failure
  - Able to isolate the fiber compressive mode sufficiently well

Literature Review- Matrix Compression

- Although no studies have focused on matrix compression it is considered in a few studies
- Assumed to be dominated be shear properties of the matrix
- Modeled as single mode II crack in 90 degree plies and subtracted from measured fracture toughness to measure the fiber compressive fracture toughness(Pinho et al 2006)
- Assumed small and negligible in comparison to the fiber damage propagation modes in some studies

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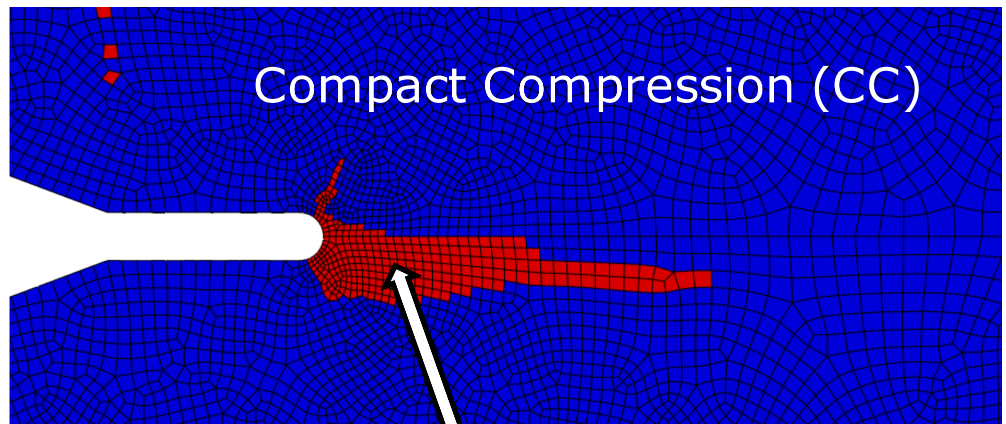
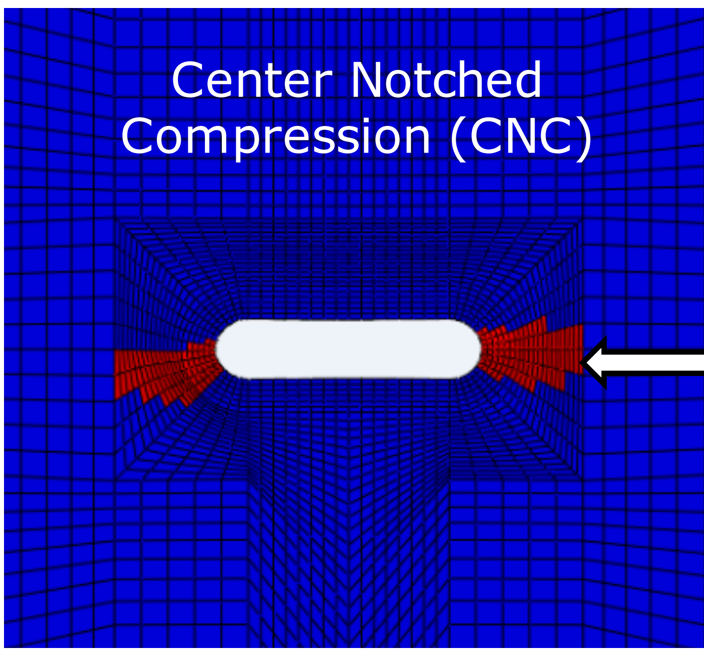
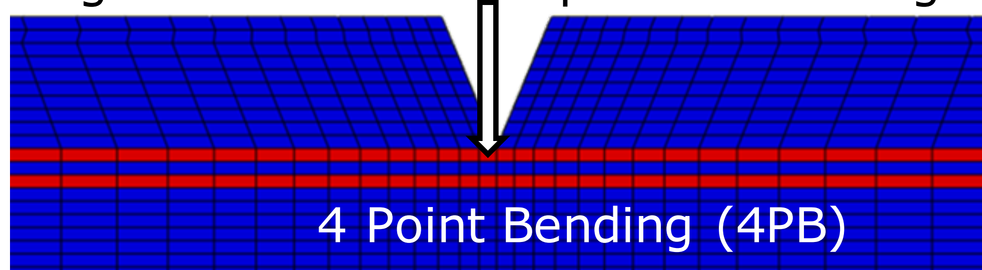
Testing Plan-Specimen Determination Study

- Modeled the three major compression specimens used in literature to determine the isolation of the matrix compression damage







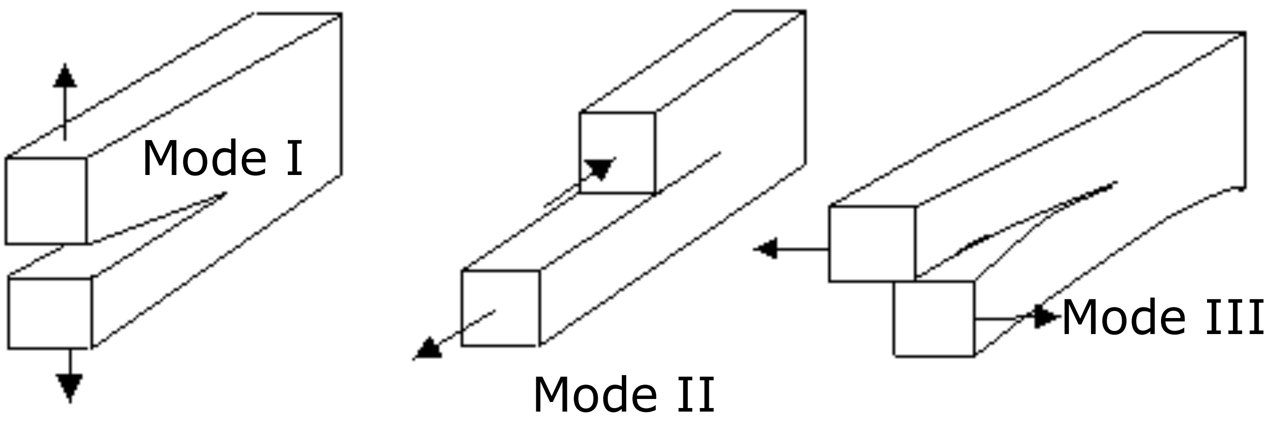
Regions of matrix compression damage

Testing Plan-Specimen Determination Study Conclusions

- Center notched compression and compact compression specimens showed fairly good isolation of matrix compression
  - CNC specimens showed tendency to fail perpendicular to notch direction when using face mounted guards
  - CC specimens showed tensile failure on opposite end and failure at load after significant damage propagation
- 4PB specimens showed significant tensile failure before much compression damage propagation
- Based on study CC specimens were determined to test fracture models based on isolation of desire damage mode and simpler fixtures than CNC specimens
- Still assumes fracture, how do we determine appropriate model?

Testing Plan- Mixed Mode Fracture

- Proposed model based on mixed mode fracture
- Compression will not propagate a crack
- Mode II will be the primary driving force for a crack
- However, need to include energy input from compressive mode I to model the material behavior
- Damage under pure compression possibly modeled as subcritical crack growth in the matrix under the mixed mode criteria



Testing Plan-Experimental Plan

- Preliminary exploratory tests before more comprehensive testing
- Unnotched Panels-Determine failure modes and if cracks form under compression loads to determine if fracture is correct model
- Compact Compression specimens
  - Vary the angle of the plies and cracks to load cracks under varied mixed mode loading conditions
  - Monitor load-displacement and crack length to determine the energy release rate
  - The energy release rate minus the frictional loses of the crack should be independent of the angle if pure mode II
  - Help classify the energy input of the compressive mode I
- Numerical models of panels and micromechanical models to assist in determining where energy is consumed during failure

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Questions?